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16. ABSTRACT

A comprehensive review is made of EPA's cooling tower plume research program with particular attention to plume modeling. The research began in 1969 with a modest effort to define the problem and continued through a multidisciplinary research project at a site where a single-cell salt-water cooling tower was installed to assess its impact on the local terrestial ecosystem. The evolutionary process involving the analyti al developments and advanced instrumentation techiniques required for such an undertaking is exaimed. Plans for continued efforts are presented.

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EPA's Cooling Tower Plume Research

By Mostafa A. Shirazi,[1] Bruce A. Tichenor,[2] and Lawrence D. Winiarski[3]

Introduction

In the United States, the electric power industry uses evaporative cooling towers at many locations for both economic and environmental reasons. The environmental side effects of wet cooling towers, both potential and real, have been the subject of research investigations at the United States Environmental Protection Agency (EPA) Laboratory in Corvallis, Oreg. Important aspects of this research are reviewed with special emphasis on the plume modeling efforts. The environmental side effects of evaporative cooling towers stem from the loss of water, both in the vapor and liquid phases. Depending on plant operation characteristics and local meteorology, from 1%-3% of the circulating water flow is lost in evaporation. Evaporation also is responsible for the concentration of dissolved and suspended materials in the circulating water. Water droplets of the same chemical composition can be entrained in the plume and leave the tower as drift.

To prevent excessive buildup of chemicals in the circulating water, small quantities are removed as blowdown and replaced with a larger quantity of makeup water. Thus, cooling towers create unique environmental effects not only through atmospheric emissions, but also from the wastewater discharge. It is beyond the scope of this paper to consider the latter effects relating to water quality. Suffice it to say that considerable research is devoted to the understanding and control of toxic chemicals in the blowdown water. Technology for water reuse is also being developed to minimize blowdown discharges.

It is useful to enumerate the potential effects of cooling towers relating to the atmospheric emission of moist and warm plumes in order to gain a perspective on the problem. This needs to be done frequently so that, in the process of

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setting priorities for research projects competing for limited resources, important problems receive proper consideration. Briefly these effects include: (1) Local ground level fogging due to increases in the water vapor content of ambient air; (2) icing of nearby roads and other structures caused by cold weather fogging and deposition of drift particles; (3) deposition of chemically laden drift particles transported out of the top of a cooling tower, especially when salt-water cooling is employed; (4) consumptive use of water caused primarily by evaporative water losses; (5) transport of undesirable material via drift when municipal or industrial wastes or agricultural runoff is used as makeup water; (6) climate modifications, such as increases in wind, precipitation, and cloud cover, due to the atmospheric discharge of heat and water vapor; and (7) acid rainout (predominantly H_2SO_4) due to the comingling of cooling tower vapor plumes with stack gas plumes. While all of these phenomenons could affect man and his terrestrial ecosystems to some degree, drift and possibly acid rainout have the greatest potential for immediate adverse ecosystem impact. Fogging and icing can cause local safety hazards, while water consumption may cause long-term deleterious effects.

Research Needs—Historical Perspective

In attempt to quantify "weather effects" in physical terms, Decker (3) observed that mixing of two air masses at different temperatures, even if both are initially saturated, results in an "apparent temperature" for which the "apparent vapor" content expressed as mixing ratio exceeds the saturation value. Equilibrium then occurs after some of the water vapor condenses. This process of condensation is responsible for the formation of minute water droplets and a visible fog. Several complicated processes are occurring simultaneously within the tower that could lead to formation of fog. According to the foregoing observation, these are: (1) Parcels of air are not totally and uniformly warmed and saturated in the tower as they pass over the packing and come in contact with the warm water films and falling droplets; (2) the mixing of differentially heated air masses causes condensation; and (3) the condensation releases heat that tends to raise the apparent temperature (Fig. 1). Consequently, only a fraction of the excess vapor at the apparent temperature will condense.

The same processes later occur outside the tower as portions of the moist warm plume mix with the cooler dry ambient air to produce fog. When fog is formed within the plume at high concentrations, precipitation may take place, causing drizzle. On their way to the ground, drizzle particles evaporate, adding the required vapor for the formation of natural ground fog. The succession of the processes of mixing, condensation, drizzle, and evaporation under relatively calm wind conditions are all conditions required for formation of fog. This means that regions with climatic conditions already conducive to natural fog formation will be most vulnerable to weather effects by cooling tower fog. Therefore, the identification of such regions in the United States was an important follow-up to this study.

While Decker and others focused on meteorological problems associated with cooling tower discharges of heat and water vapor, the subject of cooling tower drift was also receiving increased attention. Reduction in the number of sites with adequate freshwater makeup for large power plants required that salt water

be considered as an alternative source. Therefore, consideration of salt-water cooling towers was needed. Special concern was attached to the potential for vegetation damage which could be caused by salt-water drift particles. This concern focused attention on the amount of drift to be emitted from a tower and subsequently deposited on downwind vegetation. In 1970–1971, Florida Power and Light Company (FP&L) and the EPA were involved in a court case regarding the cooling system to be used at FP&L's expanded Turkey Point Power Plant.

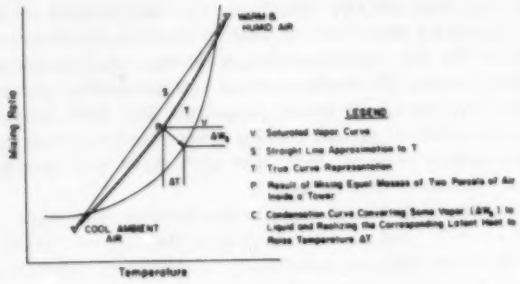

FIG. 1.—Mixing of Parcels of Air Inside Cooling Tower (3)

Legend	Fog Days	Max. Mixing Depth M	Frequency of Inversion %
H: High Potential	>45	400–600	20–30
M: Moderate Potential	>20	600	20–30
L: Low Potential	<20	600	---

FIG. 2.—Geographical Distribution of Potential Adverse Effects from Cooling Towers, Based on Fog, Low-Level Inversion, and Low Mixing Depth Frequency (11)

The court action required consideration of all available cooling systems, including salt-water cooling towers. During the court action, several disturbing observations regarding drift from salt-water cooling towers were made: (1) The total amount of drift from a cooling tower (mechanical or natural draft) could not be accurately determined with available instruments and methodology; (2) the size distribution of the drift particles could not be accurately determined; and (3) hypothetical analyses of damage caused by cooling tower salt-water drift were based on

inaccurate and unsubstantiated assumptions. These observations made it obvious that a concentrated effort had to be made to develop methods to accurately measure both drift quantity (i.e., amount emitted) and particle size distribution. Without accurate measures of these parameters, estimates of potential vegetative damage could not be made.

These initial concerns regarding the potential environmental effects of cooling towers pointed to the need for an integrated research program directed at the full range of cooling tower plume effects. The research program developed by EPA had four high priority objectives: (1) Identification of the regions in the United States most susceptible to weather modification from cooling towers; (2) development of a better understanding of the heat and mass transfer occurring within a cooling tower; (3) development of instrumentation and methodologies for measuring cooling tower plume properties and drift emissions; and (4) development of models to predict cooling tower plume and drift behavior. EPA developed a research program consistent with these four objectives. A brief review of the progress to date follows.

Climatic Conditions in United States.—An attempt was made by EG & G, Inc. (11) to identify climatic regions within the United States in terms of frequencies of meteorological conditions conducive to adverse effects from cooling tower discharges. The starting point for EG & G's analysis was the steady-state cumulus cloud dynamic model developed by Weinstein and Davis (14). Its modification for application to tower plumes includes stack height calculations, plume growth and entrainment, plume trajectory, and Gaussian diffusion downwind. The conditions for the onset of fog and haze was defined in the model as the quantity of water that the plume must add to the local environment for the air to reach saturation. The model includes analysis leading to formation of drizzle and "rain" from the plume. It does not account for evaporation from falling water droplets. From this standpoint, the model overpredicts such effects.

For typical tower characteristics and a wide range of meteorological conditions, the EG & G model was run to calculate the plume penetration and local moisture deficit conducive to fog formation. Based on evaluation of these calculations and comparisons with meteorological maps of the United States, the main areas of high potential effect were identified to be the Pacific Northwest and the Appalachian Valley. Similarly, moderate and low potential regions were identified in very general terms (Fig. 2). Specific calculations were recommended for a given site when required. The model was used initially to serve a general purpose as previously mentioned. It has since been superseded by more accurate prediction techniques.

Cooling Tower Heat and Mass Transfer.—To gain some understanding of the heat and mass transfer processes taking place within a tower, Winiarski and Tichenor (18) developed a theoretical calculation of these processes for natural draft towers that yield excellent quantitative information in general. For specific applications their model requires details of the packing characteristics. Based on loading and power plant size, the theoretical calculation can generate sufficient information for use as initial conditions for cooling tower plume models.

Instrumentation and Measurement.—Winiarski, Frick, and Tichenor (17) devised and field tested a plume sampling technique in order to measure the distribution of temperature and humidity in the invisible portion of a cooling

tower plume. A lightweight (130-g) radiosonde was attached to the tail of a small blimp that was tethered to the cooling tower and allowed to "windvane" downwind. Thus the blimp was in the same vertical plane as the plume. An operator positioned underneath the blimp traversed the radiosonde vertically through the plume by using a second lightweight line hanging from the blimp. Simultaneous sighting of the radiosonde sensor by two theodolites placed at known locations were correlated with continuously recorded temperature and humidity data transmitted from the radiosonde to the receiving station.

Measurements using this technique were made on the plumes from both single-cell and multiple-cell cooling towers. A single-cell mechanical draft salt-water cooling tower located at FP&L's Turkey Point Plant and a 10-cell freshwater cooling tower at Public Service of Colorado's Comanche Power Plant located near Pueblo, Colo., were study sites. Typical results are plotted in Figs. 3 and 4. The predicted average value shown in Fig. 3 is based on the mathematical modeling work presented in the next section.

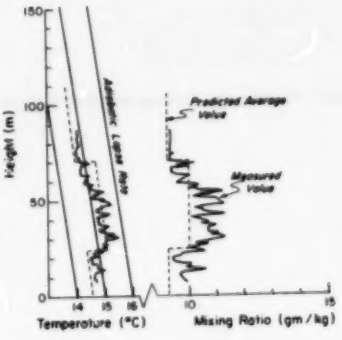

FIG. 3.—Cooling Tower Plume Data (Turkey Point) Versus Model Predictions (15)

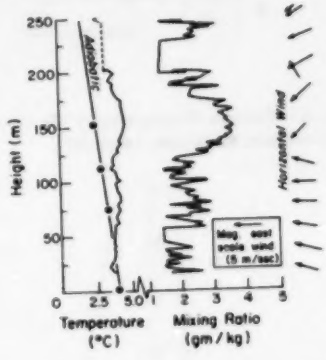

FIG. 4.—10-Cell Cooling Tower Plume Profile, Comanche Power Plant (16)

New instrumentation for measuring cooling tower drift mass and particle size distribution was developed by Environmental Systems Corporation (4,13). Using laser optic methods, the instrument was developed primarily to measure drift particles to detect the salt carryover from evaporative cooling towers using brackish water. However, the instrument can measure water droplets, irrespective of their chemical content. The working system can measure a wide range of particle sizes (50 μm-1,000 μm), the lowest limit being defined by the noise or the random but constant background fog intensity and related fog particle diameters. The upper limit is a function of the component sizes only. The system can discriminate a particle size to within 15% of its diameter and has been applied to particles of up to 50% salt content. The schematics of the equipment and typical particle density distribution measured on a commercial mechanical draft cooling tower are given in Figs. 5 and 6, respectively.

Predictive Models.—The overall objectives of the cooling tower plume modeling

program are: (1) To develop a working mathematical model that contains enough "realism" of field scale and atmospheric effects for use in estimating plume behavior, drift deposition, and icing, locally and at distance; and (2) to use this model to generate a set of nomograms that permit easy calculation of these estimates. To meet these objectives, EPA developed an integrated plume modeling effort to: (1) Examine current models and critically assess the physical assumptions involved; (2) develop detailed single and multiple plume models applicable near

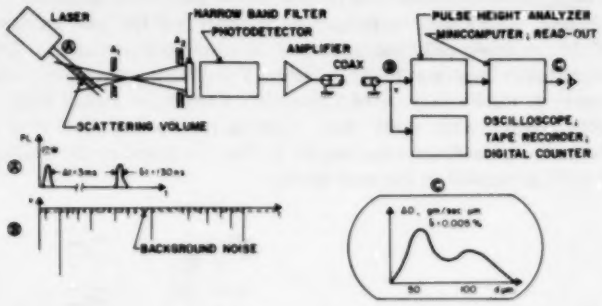

FIG. 5.—Particle Measurement Via Laser Light Scattering, Environmental Systems Corporation, Knoxville, Tenn. (4)

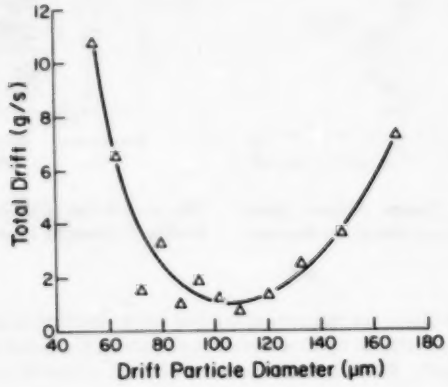

FIG. 6.—Mass Emission Histogram from Mechanical Tower (4) (Fan Diameter ≈ 8.5 m, flow, 1 m^3/s)

the source; (3) develop a less detailed model applicable to multiple tower units; and (4) obtain the extensive laboratory and field data needed to assess one or combinations of more than one model for application. A brief discription of completed and ongoing work follows.

Review and Analysis

Several good reviews are available on the subject of cooling tower plume

modeling. Winiarski and Frick (15) present a concise review on some of the more pertinent models. Many existing models are for a single source. For those few dealing with combined sources, calculations are very crude near the source. Ref. 2 contains a more detailed review of the latter subject. The scarcity of field data remains a problem that prevents adequate assessment of current models.

In addition to the review of current models, Winiarski and Frick (15) developed a simple numerical model for calculation of plume characteristics by tracing the trajectory of a "plume puff" with respect to time as it is emitted from a tower. The initial length of the plume puff in the vertical directions is similar to the tower diameter. The program satisfies conservation of mass, momentum, and energy as the plume puff rises. The emphasis in this model is on consistency in the application of conservation laws to the plume puff. To clarify this point further, consider a single dry plume subject to ambient current. In some models, the plume can be made to bend over in the direction of the ambient current more readily or less so, depending on whether the plume entrains, respectively, more or less of the ambient fluid. On the other hand, the bending of the plume also depends on the magnitude of the pressure unbalance created by the wind. The effect of this pressure unbalance is generally unknown, but it is included in some models, indirectly, by using a drag coefficient. Winiarski and Frick (15) couple the entrainment and horizontal momentum in a unique way. They assume that the wind mass available to impart its horizontal momentum to the plume is that which impinges on the plume (passes through the projected area) and that which aspirates into the plume by the shearing action due to the relative velocity of the plume with respect to the wind. They assume that this available wind mass represents an upper limit to the amount of mass that can be entrained into the plume. The horizontal momentum of this available wind mass is imparted to the plume by: (1) A portion being directly entrained into the plume; and (2) the remaining portion creating a pressure field as it deflects around the plume. By assuming that this pressure force is locally the same as the force required to decelerate all the available wind mass to the local velocity of the plume, and by inserting this force into the momentum equation, the portion of that mass which is actually entrained is calculated. Full details of the calculation procedure are contained in Ref. 15. In this manner, the local pressure force and entrainment are calculated at each step in the program. Pressure force is an important factor in determining plume trajectory near the source. Further downstream, the pressure force is small and most of the wind mass entrained comes through the projected area. When there is no wind, all the entrainment is by aspiration.

Some trajectory data are compared with calculations from this model in Fig. 7; the agreement is very good. Predicted plume dilution and plume width as shown in Fig. 3 gives a fair qualitative agreement with field data. For more detailed examination of the Winiarski-Frick model, Refs. 15 and 16 should be consulted.

Plume Interaction.—The mechanism of interaction between two neighboring plumes is not well understood. Also, it is not clear how much of this mechanism needs to be known in minute detail in order to enable a reasonable evaluation of plume effects near the tower for the purpose of evaluating plume performance further downwind. Davis (2), modified a single buoyant jet model of Hirst (6,7) to include effects of neighboring jet interaction for possible application to a

multiple-cell mechanical draft cooling tower. The analysis was for a two-dimensional line source and a dry plume. The important contribution of Davis is in the analysis of the merging processes of neighboring plumes within the zones of flow establishment and established flows of Hirst. Davis (2) also defined a merging zone to take care of asymmetry generated by interaction. In this zone, he simply assumed that the merging plumes make additive contributions

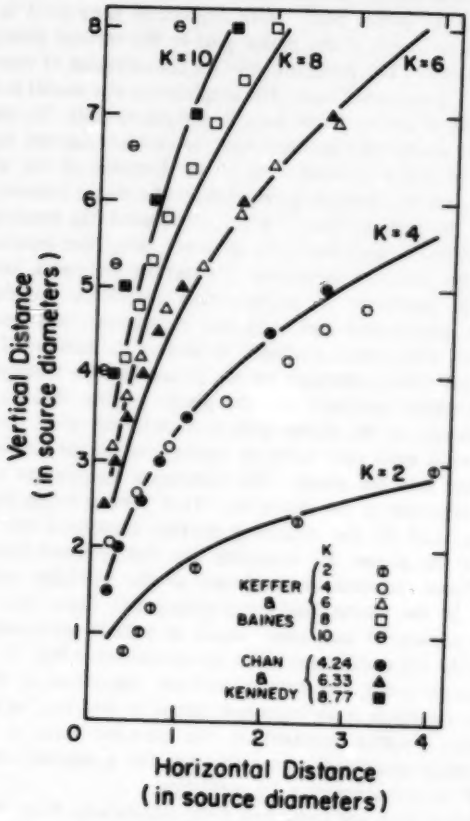

FIG. 7.—Lagrangian Puff Model Predictions Compared with Jet Data (15)

both with respect to temperature and velocity. The merging zone continues until the profiles are smooth, i.e., the difference between neighboring temperature peaks and valleys is small. Recently, Kannberg (9) collected a large set of laboratory data for a two-dimensional plume source applicable to the analysis of Davis. Kannberg (9) was able to adjust the entrainment coefficients in the model to produce very good fit with the data. Typical comparisons are shown in Fig. 8.

Effects of Tower Structure.—The mechanical draft cooling tower structure causes disturbance of the ambient wind near ground level. The suction of the ambient air at ground level further complicates the pressure field in the vicinity of the intake. During high winds, the downwind side of the tower experiences lower pressure than the upwind side, causing deflection of the plume groundward. A drag coefficient can be inserted in the plume model to correct both for the effect of the tower structure as well as the plume wake. Here, as before, data are needed to isolate effects of the wake from the structure from the possible wake of the plume itself. Since the structure is not part of the plume and since drag terms are applied to the plume alone, the interaction between the

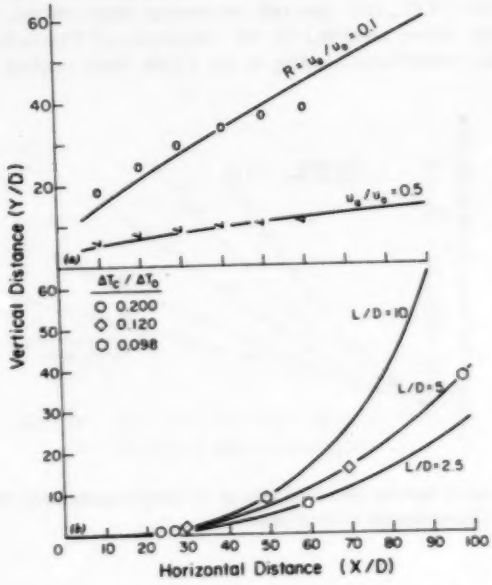

FIG. 8.—Comparison of Predicted and Measured Plume Trajectories (9): (*a*) with Vertical Discharge, R = 0.01, and 0.5, F = 11, L/D = 2.5; (*b*) with Dilution Showing Effects of Jet Spacing L Relation to Diameter D

structure and plume must be included as a changing boundary effect which is strong near the structure and negligible at a distance. A model proposed by R. C. Y. Koh at the California Institute of Technology, Pasadena, Calif., includes considerations of some of the items previously considered. Additionally, the model proposes to treat merging plumes from a cluster of cooling towers spaced in arbitrary configurations and subject to shifting wind directions. The work is in progress and no results are available yet.

Laboratory Experiments.—Laboratory experiments are being conducted at EPA's Corvallis Environmental Research Laboratory with the specific purpose of evaluating the entrainment mechanism of a buoyant jet from a three-dimensional

source. In separate experiments, simultaneous velocity and conductivity measurements are made across several plume locations downstream from a single jet, three jets, five jets, and 10 jets. The results will be analyzed to establish a relationship for entrainment as a function of downstream distance and jet aspect ratio. Preliminary results for a single jet and sample data for five jets are given in Figs. 9 and 10, respectively.

Field Experiments.—In this paper, several references have been made to the collection of plume data from mechanical draft cooling towers. The data are not completely published, but the references to them are: (1) Turkey Point, Fla., single-cell mechanical draft salt-water tower (Refs. 15, 16, and 17); (2) Comanche (Pueblo, Colo.), 10-cell mechanical draft tower (Refs. 16 and 17); and (3) Cliffside, N.C., two nine-cell mechanical draft towers, Ref. 16. EPA has also funded plume sampling by the University of Colorado (unpublished report) and has contributed funding to the Chalk Point cooling tower project

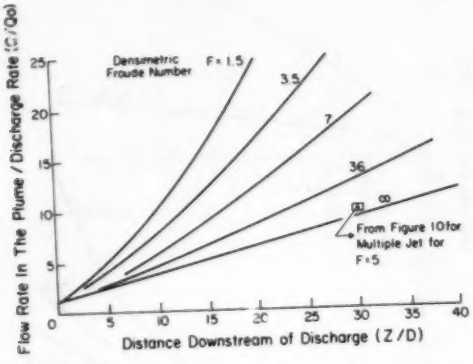

FIG. 9.—Preliminary Results Showing Effects of Initial Densimetric Froude Number on Entrainment Downstream of Discharge

in which Meteorology Research, Inc., used an instrumented aircraft to acquire in-plume data from a large natural draft cooling tower plume (19).

A research project is being conducted by Oregon State University, with cooperation from EPA and Pacific Power and Light Company (PP&L), to measure plume characteristics at PP&L's Centralia Plant in the state of Washington. There are four multicell mechanical draft towers at this site. They will be studied for a full year under a variety of environmental and operating conditions. Plans call for use of all the field and laboratory data for the development of one or combination of more than one of the aforementioned models for preparing a comprehensive workbook on cooling tower plume. This workbook will contain nomogram solutions for a wide variety of meteorological and initial source combinations. The nomograms will be suitable for application to numerous problems outlined in the introduction. These include the analysis of airborne pathogenic and toxic materials, e.g., Ref. 10. The latter problem is also being examined in an EPA contract with H_2M Corporation of Melville, N.Y.

CASE STUDY

FP&L and EPA jointly conducted a study to determine the feasibility and environmental acceptability of mechanical draft towers and spray-type modules using ocean water. The study site at Turkey Point, Fla., became a proving ground for multidisciplinary research aimed at finding how the drift from these devices affect nearby structures and vegetation. EPA scientists and scientists from Environmental Systems Corporation were involved in this study. Physical

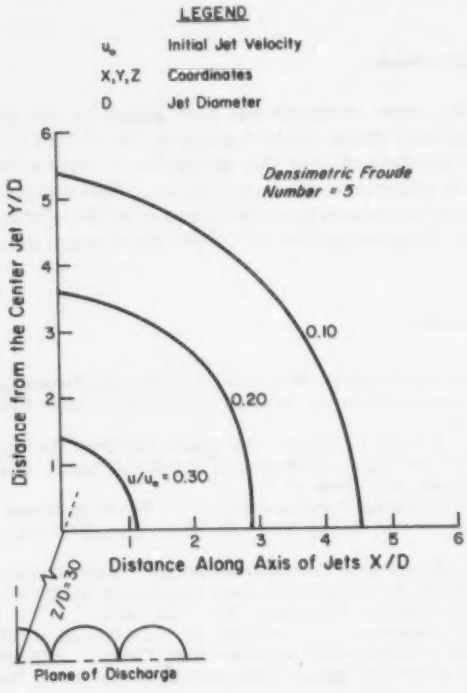

FIG. 10.—Preliminary Results Showing Distribution of Velocity Ratio in Quarter Plane 30 diam Downstream of Discharge from Row of Five Jets, D = 0.95 m Each, Placed Side by Side

measurements of the plume, drift measurements from the tower, background meteorological and salt drift measurements, ground deposition near the tower as well upwind from it, and physiological measurement of effects on vegetation were all undertaken in a comprehensive coordinated effort. Results have been published in several volumes. It is outside the scope of this paper to detail the findings or the procedures. Briefly, drift data are reported in Ref. 12, plume data in Refs. 15 and 17, vegetation data and results in Ref. 5, and statistical analysis of physical data in Ref. 8. It was found, according to the last reference,

that the operation of the single-cell cooling tower at Turkey Point did not increase the background salt concentration by a statistically significant amount at any sampling station. The operation of the spray module, except at one station, showed no significant increases either. Furthermore, Hindawi, Raniere, and Rea (5) found no effects attributable to salt aerosol emissions from test cooling devices on indigenous plants, soil, or local freshwater sampled during or following operation of test cooling tower spray modules. This study involved only a single-cell tower and a few spray modules; therefore, the results can not be directly extrapolated to a full complex of multiple-cell towers without some uncertainty.

Summary and Conclusions

Throughout this paper, emphasis has been placed on the integrated nature of EPA's cooling tower plume research program. The Turkey Point Power Plant is an illustrative example of how this integration is implemented. This paper reviews the EPA research program on cooling tower plumes, Investigations by non-EPA supported research have also been conducted and should be consulted to obtain a more complete picture of United States research on this problem (1).

Appendix.—References

1. "Cooling Tower Environment—1974," *ERDA Symposium Proceedings, CONF-740302*, National Technical Information Service, United States Department of Commerce, Springfield, Va.
2. Davis, L. R., "Analysis of Multiple Cell Mechanical Draft Cooling Towers," *EPA-660/3-75-039*, United States Environmental Protection Agency Ecological Research Series, Washington, D.C., June, 1975.
3. Decker, R. W., "Cooling Tower and Weather," *Report to Federal Water Pollution Control Administration*, Oregon State University, Corvallis, Oreg., Feb., 1969 (out of print).
4. "Development of Low-level Drift Instrumentation," *Water Pollution Control Series 16130 GNK 10/71*, Environmental Systems Corporation for United States Environmental Protection Agency, Washington, D.C., Oct., 1971.
5. Hindawi, A. T., Raniere, L. E., and Rea, G. A., "Ecological Effects of Aerosol from Salt Water Cooling Systems at Turkey Point, Florida," *EPA-660/3-75-011*, U.S. Environmental Protection Agency, Ecological Research Series, Washington, D.C., Oct., 1975.
6. Hirst, E. A., "Analysis of Buoyant Jets Within the Zone of Flow Establishment," *Oak Ridge National Laboratory Report TM-3470*, Oak Ridge, Tenn., 1971.
7. Hirst, E. A., "Analysis of Round Buoyant Jet Discharge to Flowing Stratified Ambients," *Oak Ridge National Laboratory Report 4685*, Oak Ridge, Tenn., 1971.
8. Hunter, H. E., "Effects of Mechanical Cooling Devices on Ambient Salt Concentration," *EPA-600/3-76-034*, United States Environmental Protection Agency Ecological Research Series, Washington, D.C., Apr., 1976.
9. Kannberg, L. D., "An Experimated/Analytical Investigation of Deep Submerged Multiple Buoyant Jets," thesis presented to Oregon State University, at Corvallis, Oreg., in July, 1976, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
10. Lighthart, B., and Frisch, A. S., "Estimation of Viable Airborne Microbes Downwind from a Point Source," *Applied and Environmental Microbiology*, Vol. 31, No. 5, May, 1976, pp. 700–704.
11. "Potential Environmental Modification Produced by Large Evaporative Cooling

Towers," *Water Pollution Control Series* 16130 DNH *01/71*, EG&G, Inc., for United States Environmental Protection Agency, Washington, D.C., Jan., 1971.
12. Schrecker, G. O., et al., "Drift Data Aquired on Mechanical Salt Water Cooling Devices," *EPA-650/2-75-060*, Environmental Protection Technology Series, United States Environmental Protection Agency, Washington, D.C., July, 1975.
13. Shofner, F. M., "Explicit Calibration of Pills II System," *EPA-660/2-73-011*, Environmental Protection Technology Series, United States Environmental Protection Agency, Washington, D.C., Sept., 1973.
14. Weinstein, A. I., and Davis, L. G., "A Parametrized Numberical Model of Cumulus Convection," *National Science Foundation Report No. 11, NSF GA-77*, Department of Meteorology, Pennsylvania State University, University Park, Pa., 1968.
15. Winiarski, L. D., and Frick, W. F., "Cooling Tower Plume Model," *EPA-600/3-76-100*, Ecological Research Series, United States Environmental Protection Agency, Washington, D.C., Sept., 1976.
16. Winiarski, L. D., Frick, W. F., "Field Investigation of Mechanical Draft Tower Plumes," *EPA 600/7-77-025*, U.S. Environmental Protection Agency, Washington, D.C., 1977.
17. Winiarski, L. D., Frick, W. F., and Tichenor, B. A., "Cooling Tower Plume Measurements," *Report #75-CH 1004-1 ICESA*, Institute of Electrical and Electronic Engineers, New York, N.Y., 1976.
18. Winiarski, L. D., and Tichenor, B. A., "Model of Natural Draft Cooling Tower Performance," *Journal of the Sanitary Engineering Division*, ASCE, Vol. 96, No. SA4, Proc. Paper 7461, Aug., 1970, pp. 927-943.
19. Wooffinder, G. J., Anderson, J. A., and Harrison, P. A., "Aircraft Survey, Chalk Point Cooling Tower Plume—December 1975," *Report #76R-1410*, Meteorology Research, Inc., Altadena, Calif., Mar., 1976.